

Cathodic Vacuum Arc Plasma of Thallium

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Abstract

Thallium arc plasma was investigated in a vacuum arc ion source. As expected from previous considerations of cathode materials in the Periodic Table of the Elements, thallium plasma shows lead-like behavior. Its mean ion charge state exceeds 2.0 immediately after arc triggering, and diminishes to the predicted 1.60 and 1.45 after about 100 μ s and 150 μ s, respectively. The most likely ion velocity is initially 8000 m/s and decays to 6500 m/s and 6200 m/s after 100 μ s and 150 μ s, respectively. Both ion charge states and ion velocities decay further towards steady-state values, which are not reached within the 300 μ s pulses used here. It is argued that the exceptionally high vapor pressure and charge exchange reactions are associated with the establishment of steady-state ion values.

Keywords: Cathodic vacuum arcs, thallium, ion charge states, ion velocity

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Cathodic vacuum arc plasmas are characterized by plasma production at small mobile cathode spots: the cathode is the feedstock material for the plasma [1, 2]. The species of the plasma are determined by the selection of the conductive material serving as the cathode material. Such material can be any metal or metal alloy, semimetal, or highly doped semiconductor, as long as it is sufficiently conductive to serve as the cathode. The anode is merely an electron collector as long as the arc current is low (about 1 kA or less, no anode spots) and its temperature is low enough such that evaporation is insignificant.

Cathodic arc plasmas have been investigated extensively. It is well established that many arc discharge and plasma parameters show periodicity according to the cathode material's place in the Periodic Table of Elements [3-5]. Some of the materials, however, have rarely or never been measured because they are either extremely rare (e.g. Tc, Os), radioactive (e.g. Tc, Ac, Pu), difficult to handle due to their high chemical reactivity (e.g. Rb, Cs, Fr), or toxic (e.g. Tl). Nevertheless, the charge state distributions of these plasmas can be approximately predicted by the position of the cathode material in the Periodic Table combined with simplified modeling [3-5].

In this Technical Note, we report about the production of thallium plasma and measurements of its ion charge states and ion velocities. We will compare the experimental results with previous predictions.

Thallium, element 81, is a soft, lead-like metal; some of its physical properties are mentioned in Table 1 and compared to lead. Thallium and its compounds are highly toxic acutely and chronically, which prevents wide application of this material.

However, certain semiconductor doping concepts propose the use of thallium by ion implantation. This was the initiating force to explore thallium plasmas.

To ensure best comparison with the results of other materials, thallium arc plasma was produced in the same vacuum arc ion source setup used previously, allowing us to measure arc current and voltage, and the ion charge state distribution and ion velocities, all in a time resolved manner [5]. The Tl cathode was a rod of 9 mm diameter and 40 mm length, clamped in a water-cooled holder. The cathode spots could only burn on the rod's front side because the rod was inserted into an alumina ceramic tube. An annular anode with an inner diameter of 1.25 cm was placed downstream of the cathode, allowing a large fraction of the plasma plume to stream towards an ion extraction grid system. The extracted ions were used for charge state analysis based on the time-of-flight principle. The arc was fed by a pulse-forming network giving approximately rectangular current pulses with an arc current of 400 A for 300 μ s, at a repetition rate of 3 pulses per second. The ion extraction voltage was 40 kV and the arcs were operated at a vacuum base pressure of about 10^{-4} Pa. For more details of the experimental setup, ion extraction and time-of-flight analysis, the reader may consult the literature on vacuum arc ion sources, especially on the "Mevva V" ion source [6, 7] and its use for short pulse ion production [5].

Measurements of the charge state distribution revealed that not just the solid metal but also the plasma is similar to lead. Fig. 1 shows the ion charge state spectrum, containing only charge states one and two. By appropriately delaying the gate signal of the time-of-flight spectrometer with respect to the beginning of each arc pulse, the time evolution of the charge states can be investigated. Fig. 2 shows that the mean ion charge

state decays towards a steady-state value, although that value is not reached within the limited time of the arc pulses used.

The circuit of the pulse-forming-network was modified such as to obtain oscillations in the arc current that can be used as markers in the ion current. This can be used to determine the most likely ion velocity as a function of time (the technique has previously been used for other cathode materials [8]). The result is also included in Fig. 2. One can see that the ion velocity is high at the beginning of each arc pulse and decays towards a steady-state value, which is also not reached within the arc pulse duration. The rates of decay of the ion charge state and the ion velocity are very similar, indicating that these decays may have a common cause.

A possible reason for charge state decay and reduction of ion velocities can be the evolution of neutral density in the volume between the cathode and the ion extraction grids [9]. The ions formed by the cathode spot processes may interact with the neutrals via charge exchange collisions. While charge exchange collisions conserve charge, the average ion charge state is lowered if multiply charged ions are involved, which is due to the fact that previous neutrals are now included in the ion charge accounting. The average charge evolution is affected by the concentration of neutrals, which have several sources: cooling cathode spot craters, evaporating macroparticles, and non-sticking (neutralized) ions that bounce back from walls. The role of neutrals is especially large for Tl due to its high vapor pressure (Table 1).

Finally, we compare the results obtained with the predictions based on element grouping in the Periodic Table. It was calculated [3] that Tl has an expected average ion charge state of about 1.6, which is very well within the measured data range. The

original estimates were based on comparable results measured at about 100-150 μ s after arc initiation; considerations based on the cohesive energy rule [8] predicted that the values are a little lower than comparable values for lead. The agreement is good, although further decay with time to lower values is very significant for thallium.

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Figure Captions

Fig. 1 Time of flight spectrum for thallium arc plasma, as measured for 400 A, with a repetition rate of 3 p.p.s., at 150 μ s after arc initiation.

Fig. 2 Evolution of the most likely ion velocity and the average ion charge state after arc initiation (Tl arcs, 400 A, 3 p.p.s).

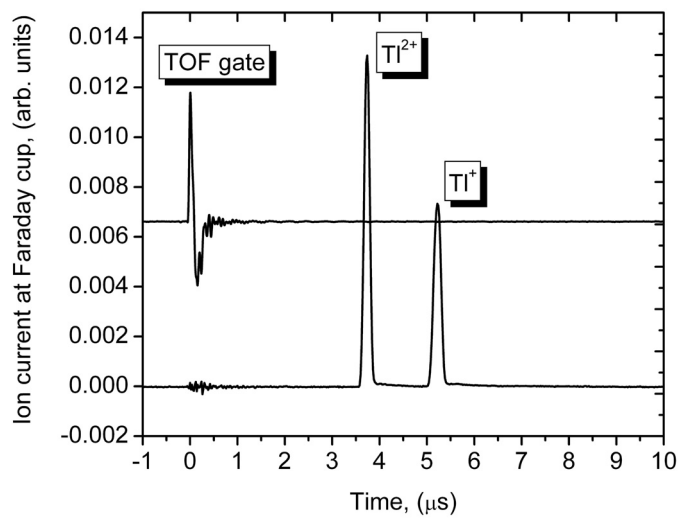


Fig. 1

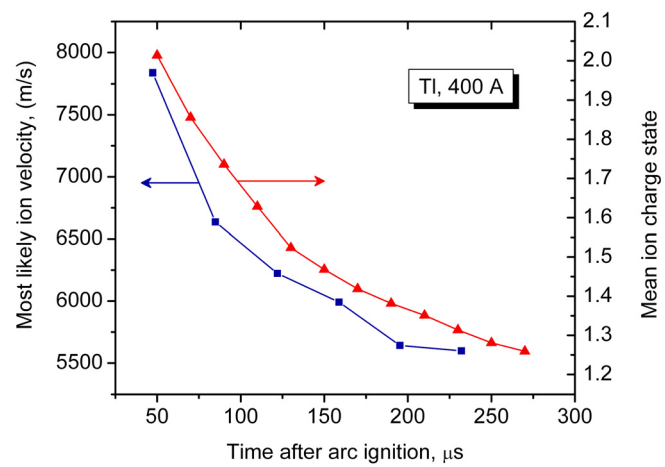


Fig. 2

Table 1 Physical properties of thallium metal and thallium vacuum arc plasmas. For comparison, the data for lead are given, too, which are very similar except the vapor pressure.

	Tl	Pb (for comparison)
Atomic mass	204.37	207.19
Density (g/cm ³)	11.85	11.34
Melting point (°C)	304	327
Boiling point (°C)	1457	1740
Cohesive energy (eV/atom)	1.88	2.03
Thermal conductivity (W/m K) @ 20°C	46	35
Electrical resistivity (nΩ m)	180	208
Vapor pressure (Pa) @ 1000°C	1100	150
Mean ion charge state after 150 μs	1.45	1.6
Most likely ion velocity (m/s)	6000	5800
Most likely kinetic energy after 150 μs (eV)	37	36